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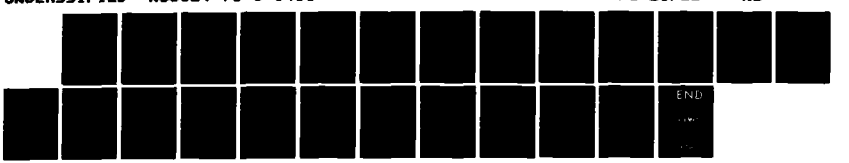

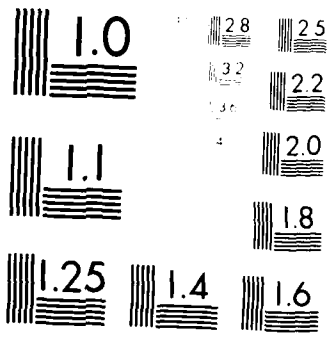

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Technical Report No. 37

AN IMPROVED TORSIONAL METHOD FOR DETERMINING THE FRACTURE TOUGHNESS OF STIFF MATERIALS AND OF ADHESIVE JOINTS

by

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report No. 37	2. GOVT ACCESSION NO. AD-A152 091	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) An Improved Torsional Method for Determining the Fracture Toughness of Stiff Materials and of Adhesive Joints		5. TYPE OF REPORT & PERIOD COVERED Technical Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) K. Cho and A. N. Gent		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-0408
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute of Polymer Science The University of Akron Akron, Ohio 44325		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 092-555
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Power Program Arlington, VA 22217		12. REPORT DATE March, 1985 13. NUMBER OF PAGES 21
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Submitted for publication in: International Journal of Fracture

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Adhesion, Adhesive joints, Double-torsion test, Fracture energy, Polymers, Strength, Torsion.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A simple modification is described of the Outwater torsion test method for determining the fracture energy of stiff materials and of adhesive joints. It permits large torsions to be applied and the corresponding torque to be simultaneously monitored. The modified test method can be used with specimens of simple rectangular shape and having a wide range of stiffness. As an example, the fracture

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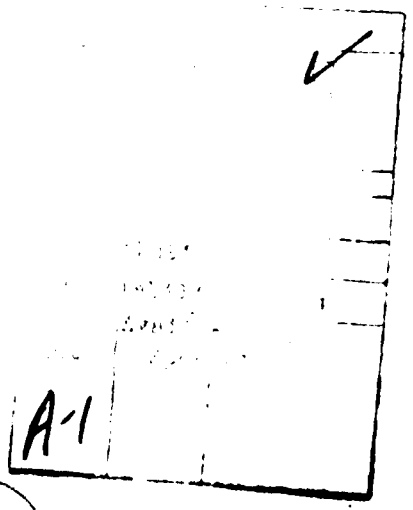
energy is determined for molded rectangular bars of polystyrene having a wide range of thickness and of width.



1. Introduction

A simple torsional test method, developed by Outwater and Gerry (1) and utilized by Kies and Clark (2) and Evans (3), has several advantages when used for measuring the fracture energy (toughness) of relatively stiff materials and adhesive joints. The first advantage is that it employs simple flat rectangular specimens. Secondly, the imposed failure force remains constant, at least in principle, while the crack is driven forward over long distances, so than an average strength can be readily determined. Thirdly, the fracture energy is given directly in terms of the specimen dimensions, its stiffness during loading, and the critical load at which the crack propagates. No other measurements are necessary, therefore, to determine the work G_c of fracture, or the work G_a of separation, per unit area cracked through.

The test method as commonly used is shown schematically in Figure 1. A rectangular specimen of length L, width W and thickness T is grooved along the center of one face, generally the lower one, and pre-cracked to a distance C_o. It is then subjected to three-point bending by a test device, as shown in Figure 1, so that the applied load P imposes a torque on each arm of the specimen formed by the pre-crack.

Assuming that the material is linearly-elastic and that the arms are sufficiently long to be placed in a state of simple torsion by the applied torque, then P will be proportional to the vertical displacement d of the point of load application and inversely proportional to the length C of the crack. Thus,

$$P = k\, d/C, \qquad (1)$$

where k is a constant representing the stiffness of the specimen when the arms have unit length. Strain energy W is stored in the two

twisted arms, of amount

$$W = \frac{1}{2} Pd = \frac{1}{2} kd^2/C. \qquad (2)$$

The Griffith criterion for advance of the crack is that the loss in strain energy incurred by crack growth is more than sufficient to meet the requirement for propagation. Thus,

$$-[\partial w/\partial c]_d \geq T' G_c \quad \text{or} \quad T' G_a, \qquad (3)$$

where T' denotes the thickness cracked through. (T' is less than the specimen thickness if a groove is made initially to guide the crack along the center line.) The fracture energy G_c or G_a is obtained from equations 2 and 3 in terms of the critical force P_c at which the crack advances:

$$G = P_c^2/2kT'. \qquad (4)$$

Measurements of the stiffness k of the assembly as the load is applied and the critical load P_c at which the crack advances are thus sufficient to determine the value of G, at least in principle.

Unfortunately, three-point bending is only a useful loading system over a restricted range of specimen stiffness. If the specimen is extremely stiff, comparable to the stiffness of the test machine, then the potential energy released by crack growth is sufficient to cause catastrophic fracture. On the other hand, when the specimen deforms to a substantial extent under the applied load, then the relation between P and d becomes a non-linear one and equation 4 is no longer applicable. Also, the application of a bending load is experimentally difficult when the specimen deforms significantly.

In order to circumvent these difficulties, a new way of imposing torsional strains on the two arms of the Outwater specimen has been devised, based on the recently-proposed method for imposing large

bending deformations (4). It is described below. Some experimental measurements of the fracture energy of molded rectangular bars of polystyrene are also given, to illustrate its potential use.

2. Proposed test method for large torsional deflections.

The proposed test method is shown in Figure 2. The test specimen is now secured by two clamps which grip the ends of each arm. One clamp is fastened to a vertical pulley, with the pulley axle arranged to be in line with the axis of the specimen. The pulley axle is supported in fixed bearings, mounted on the floor of a conventional tensile testing machine. Rotation of the pulley is then imposed by a flexible cable passing around it, attached to the moveable cross-head of the test machine.

The second clamp is attached to one end of a long rigid light-weight bar. The other end is suspended from a tensile load cell by means of a long vertical cable. Thus, the second clamp is free to move horizontally or vertically, at least over short distances, but is completely prevented from rotation by the rigid bar and inextensible cable.

Vertical movement of the crosshead through a distance y imposes a corresponding angular rotation θ on one clamp with respect to the other,

$$\theta = y/r \tag{5}$$

where r denotes the pulley radius. The corresponding torque M applied to the specimen is proportional to the tensile force F registered by the load cell:

$$M = Fa \tag{6}$$

where a denotes the moment arm, i.e., the horizontal distance between

the line of action of the vertical load-cell cable and the central line of the test specimen, Figure 2.

The analysis leading to equation 4 can be carried out in an analogous way for torsional deflections and yields the result:

$$G = M_c^2 / 2 k_t T' \qquad (7)$$

where M_c denotes the critical value of the applied torque at which the crack propagates and k_t denotes the torsional stiffness of the test system for unit length of the arms:

$$k_t = MC/\vartheta. \qquad (8)$$

Thus, as before, the fracture energy G can be determined using only the critical applied torque M_c and the torsional stiffness k_t of the test specimen before fracture was initiated, Figure 3. But now the deflection ϑ can be relatively large, approaching 180°, before the test must be discontinued. And the applied force itself will be relatively small, even for stiff and strong specimens, if the moment arm a is relatively long, so that the compliance of the test machine becomes unimportant.

3. Fracture energy of molded polystyrene bars

Rectangular bars of various dimensions were molded from pellets of clear polystyrene (Styron 685, Dow Chemical Company) by pressing them at 140°C for about 30 min. The sheets obtained in this way were free from bubbles and non-birefringent, indicating little or no residual strain. Test pieces were prepared from these molded bars by machining a v-shaped groove along the center line of one surface, and by inserting an initial crack at one end by sawing. The tip of the saw cut was sharpened by pressing a razor blade into the material.

If this step was not taken, it was found that the original blunt crack grew catastrophically at a relatively high value of the applied torque, whereas a sharpened initial crack was found to grow smoothly and continuously at a well-defined value of the applied torque. It was also found advantageous to make the initial crack length C_o comparable to or greater than the width $W/2$ of the testpiece arms, and to make the depth of the v-shaped groove not more than about one-half of the testpiece thickness T.

Results obtained with testpieces having a wide range of thickness T, and hence fractured thickness T', and with a wide range of width W , are given in Table 1. Because of the wide range of dimensions employed, the torsional stiffness coefficient k_t was found to vary by a factor of over 100X and the critical torque M_c at which the crack propagated was also found to vary by a large factor, about 40X. Nevertheless, values of the fracture energy G_c calculated by means of equation 7 from the measured fracture torque and specimen stiffness coefficient were found to be relatively uniform, with a mean value of 1.23±0.5 kJ/m^2. Moreover, this value is in good agreement with values obtained previously for polystyrene by a variety of methods, ranging from 0.5 kJ/m^2 to 3.0 kJ/m^2 (5-7). This general consistency indicates that the proposed test method gives correct values for the fracture energy, and can be used with testpieces of quite varied dimensions.

4. Fracture energy of adhesive joints

The fracture energy G_a required to separate an adhesive from a substrate can also be determined in the same way. Two possible specimen arrangements are shown in Figure 4. In either case it is necessary that one or both of the adhering rectangular blocks is able to undergo

a significant amount of torsion so that torsional strain energy can be made available for fracture. It is not necessary, however, that the specimen be symmetrical in form or that the adhesive itself be the "soft" member for equation 7 to apply.

Acknowledgement

This work was carried out while one of the authors (A.N.G.) was a guest worker in the Polymers Division of the National Bureau of Standards, Washington, D.C. Acknowledgement is due to Dr. L.C. Smith, head of the Polymers Division and Dr. D.L. Hunston, head of the Composites Section, for their kind hospitality during this stay.

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Table 1: Measurements of fracture energy G_c for molded polystyrene bars.

Testr ece dimensions				Stiffness	Critical torque	Fracture energy
W	T	T'	C	$k_t \times 10^3$	M_c	G_c
(mm)	(mm)	(mm)	(mm)	(Nm²/rad)	(Nm)	(kJ/m²)
20	1.13	0.52	40	2.0	0.043	0.9
20	2.39	0.94	40	8.5	0.13	1.1
20	3.79	1.90	33	42.1	0.39	1.0
40	1.13	0.55	29	3.6	0.056	0.8
40	1.35	1.14	29	4.1	0.078	0.7
40	1.99	0.67	31	12.1	0.119	0.9
40	2.99	1.15	26	13.4	0.234	1.8
40	3.79	1.62	26	70.0	0.563	1.4
40	5.41	2.79	27	160.0	1.19	2.0
60	1.13	0.52	28	4.1	0.045	0.7
60	1.99	0.54	31	10.9	0.124	1.3
60	3.79	1.76	30	103.0	0.66	1.2
60	5.50	2.92	36	289.0	1.90	2.2

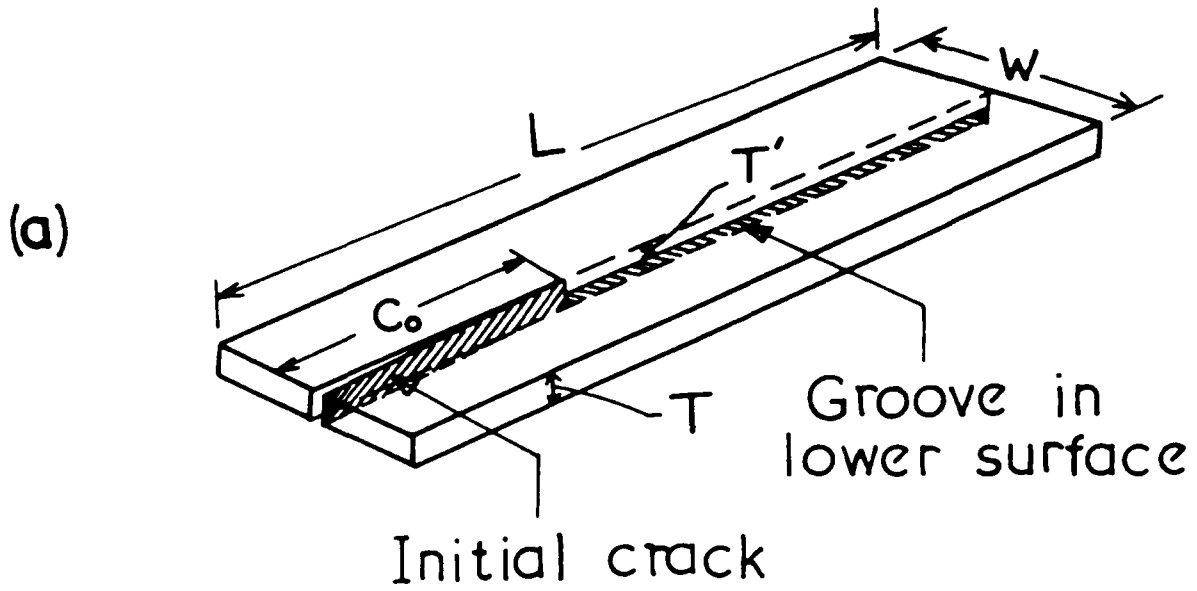
Figure Legends

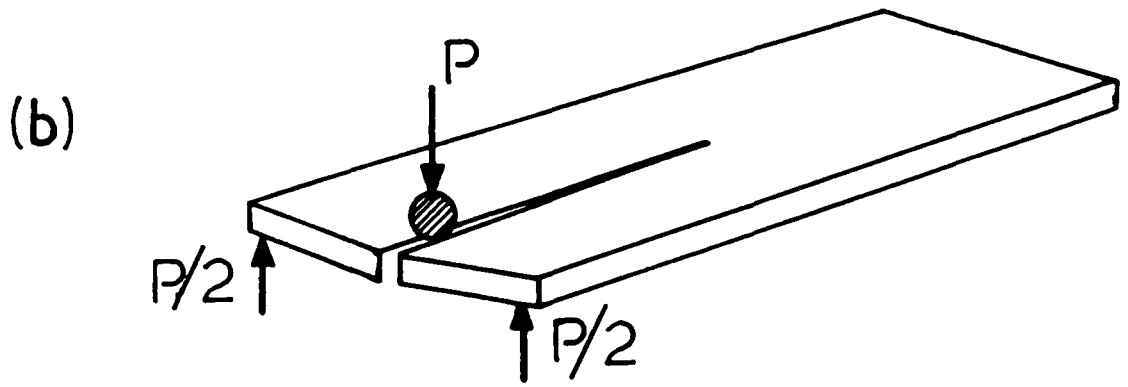
Figure 1. (a) Sketch of rectangular Outwater specimen, pre-cut along the center line for a distance C_o and grooved along the center line in the lower surface.
(b) Three-point bending method of applying torques to the specimen arms.

Figure 2. Proposed method of applying torques to the arms of an Outwater specimen, taken from reference 3.

Figure 3. Sketch of an experimental relation between applied torque M and pulley rotation ϕ, showing fracture torque M_c and method of determining stiffness coefficient k_t.

Figure 4. Two specimens suitable for determining the fracture energy G_a for an adhesive joint.
(a) With a rectangular plate of adhesive edge-bonded to a rectangular plate of the substrate material.
(b) With two rectangular plates of the substrate material edge-bonded together with a layer of adhesive.





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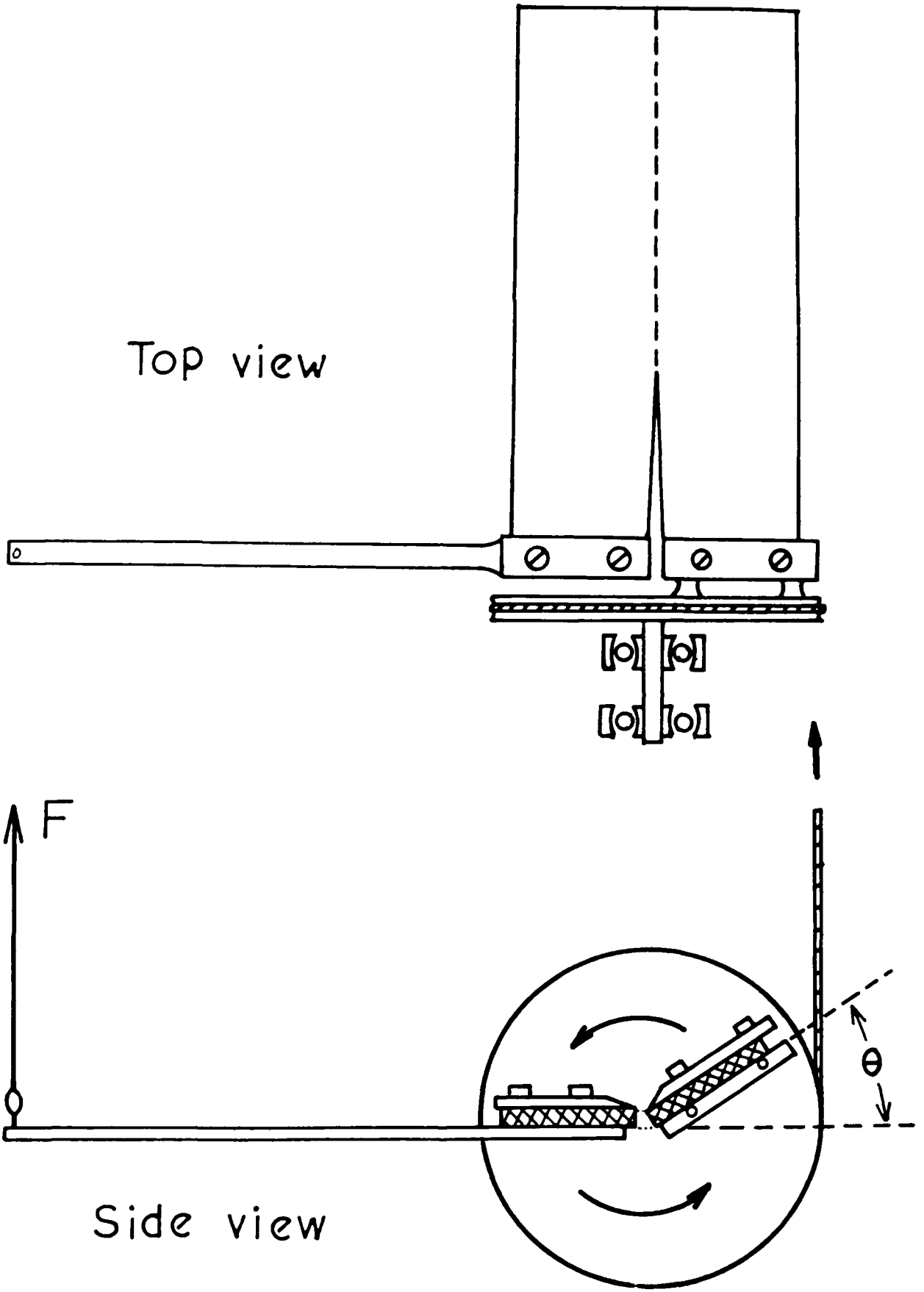

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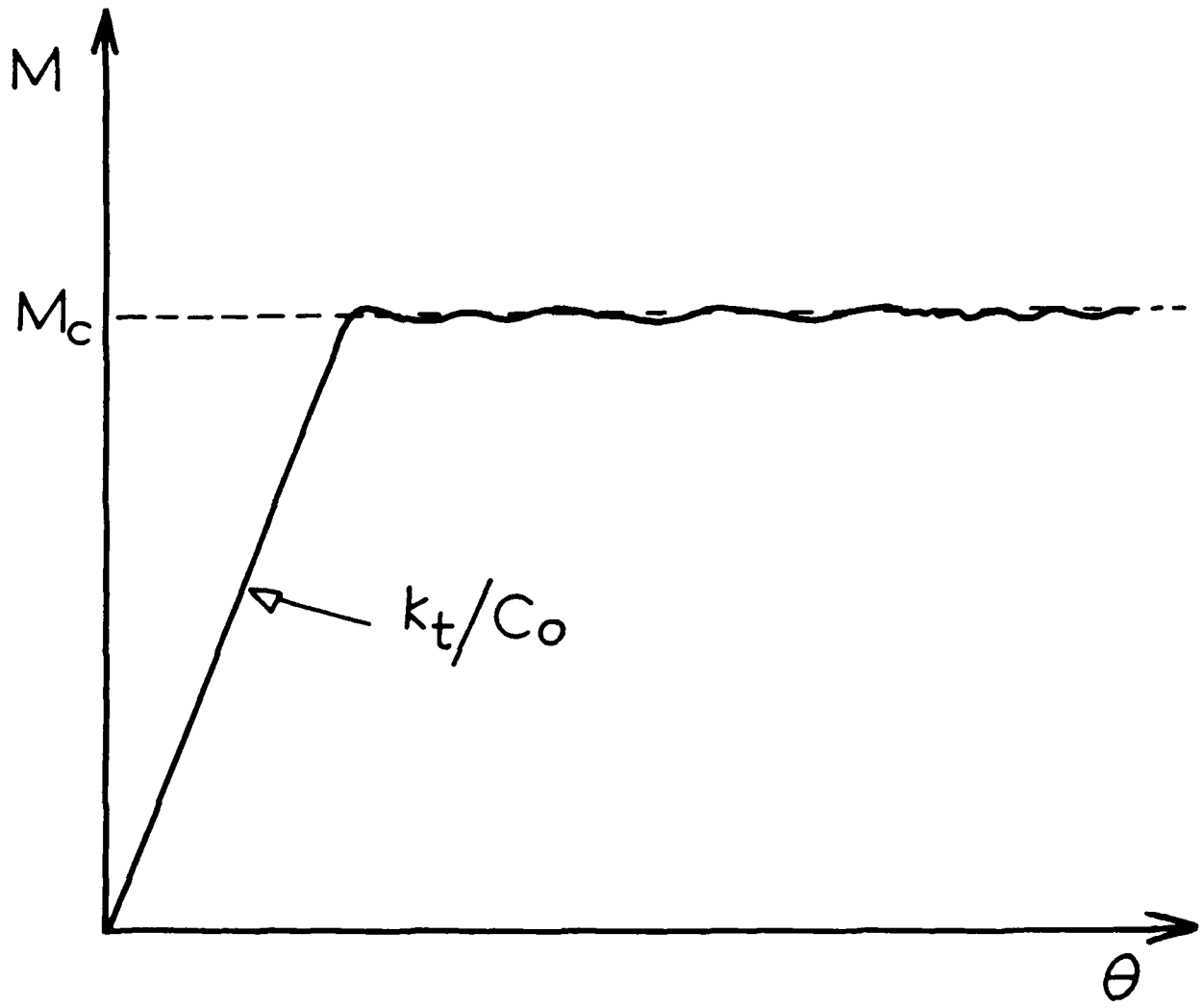

Figure 3

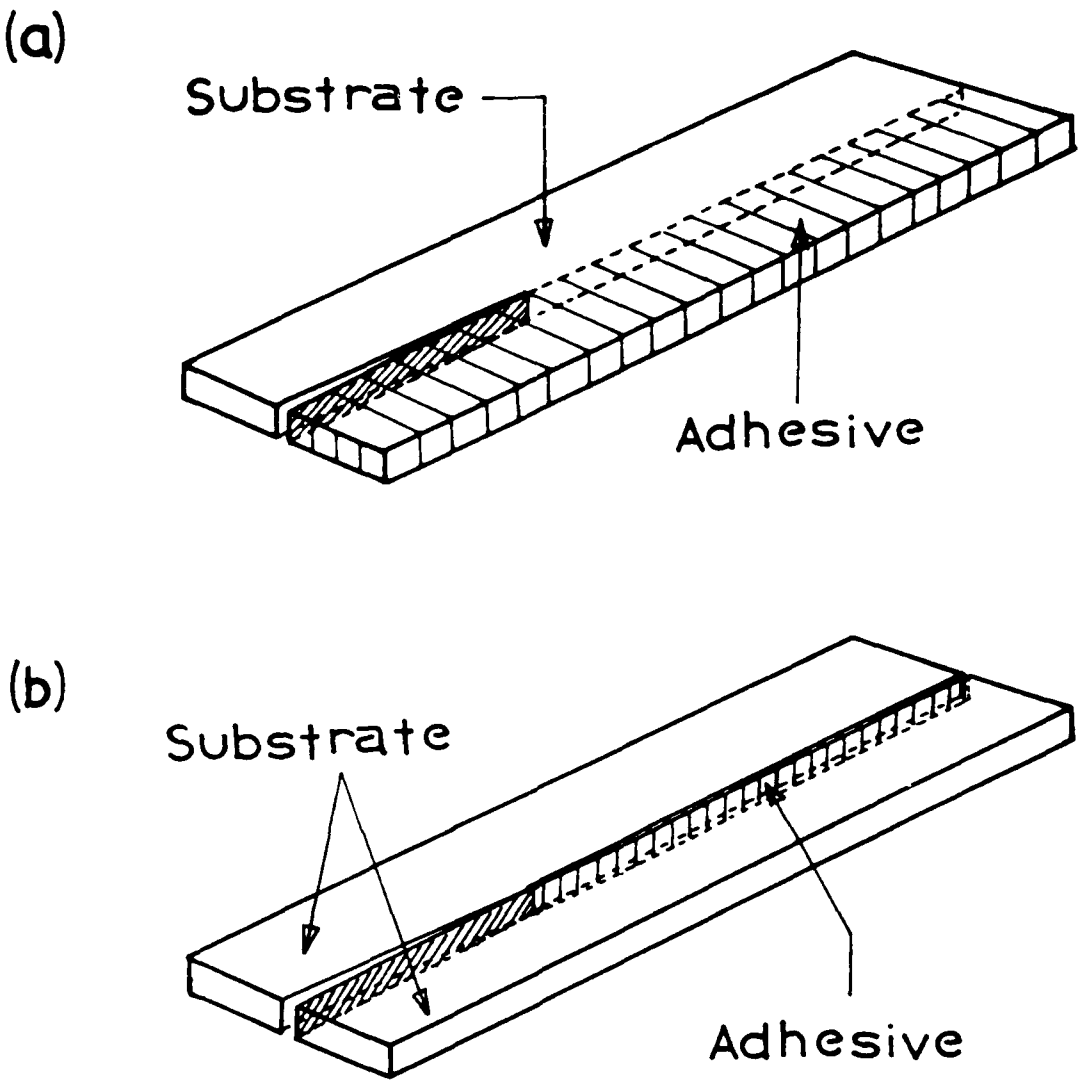

Figure 4

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